Detection of weakly interacting light vector bosons by coherent scattering

A. Ljubičić [1] and D. Kekez

Ruđer Bošković Institute, Bijenička 54, 10000 Zagreb, Croatia

We propose a novel experimental method to produce and detect weakly interacting light vector bosons using coherent processes in refractive media. A light vector boson would be produced by a laser photon scattered at a plane interface between two media of different dielectric properties and will be converted back to photon in the similar scattering process. The effect depends strongly on the indices of refraction of the two media. If incident and recovered photons were traveling through extremely high vacuums, limits on the existence of several light vector bosons could be substantially improved.

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[1] E–mail address: Ante.Ljubicic@irb.hr

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The existence of weakly interacting light bosons could be of considerable significance in improving our understanding of many phenomena. For example, such pseudoscalar particles as axions [1] and majorons [2], could make contributions to the missing mass of the universe and could also be involved in explanations of possible neutrino masses. Hypothetical spin 1 baryonic [3] and leptonic [4] photons are candidates to be the quanta of any "fifth" force field, and photon-paraphoton oscillations [5] could resolve the discrepancy between the observed cosmic background and pure blackbody radiation [6]. The discovery of gravitons, tensor particles with spin 2, or antigravitons, vector particles with spin 1, would be particularly exciting and would be fundamental in the construction of a quantum theory of gravitation.

For the detection of massless or nearly massless weakly interacting light vector bosons we propose a novel experimental method based on coherent processes in refractive media. The behaviour of visible photons in refractive media is determined by Rayleigh scattering and a Feynman diagram of this process is shown in Fig. 1a. Rayleigh scattering is an elastic process and the total amplitude for the process is a coherent sum of scattering amplitudes on many scattering centers. In addition to the Rayleigh scattering there is also an elastic process in which a photon is absorbed and a weakly interacting light vector boson is emitted. A Feynman diagram for this process is shown in Fig. 1b. Weakly interacting light spin 1 particles are denoted with ξ. In refractive media the scattering amplitudes for this process also add coherently and the weakly interacting vector bosons behave like photons in the sense that they are emitted in both directions at the interface between two refractive media, the backward emission corresponding to reflection and the forward emission to refraction.

We would like to calculate the intensities of reflected and refracted beams for the processes shown in Fig. 1. If a_{fi} is the scattering amplitude for a single scatterer placed at the origin of a coordinate system then the scattering amplitude for a single scatterer at an arbitrary position $\vec{r}$ will be $a_{fi}(\vec{r}) = a_{fi}\exp(-i\vec{q}\vec{r})$, where $\vec{q} = \vec{k}_i - \vec{k}_f$ is a vectorial change of the wave vector. If the scatterers are densely packed so that the average distance d between two scatterers satisfy the condition $qd \ll 1$, the total amplitude could be obtained by integrating contributions from all scatterers,

$$A_{fi} = a_{fi} \int d^3r \mathcal{N}(\vec{r}) \exp(-i\vec{q}\vec{r}) \tag{1}$$

In relation (1) $\mathcal{N}(\vec{r})$ is a realistic distribution of the scatterer number density. For two refractive media with well defined scatterer number densities N and N', $\mathcal{N}(\vec{r})$ could be represented with the well-known step function θ. If the plane surface between two media is in the x, y plane, than the density distribution $\mathcal{N}(\vec{r}) = N\theta(-z) + N'\theta(z)$ acquires constant values N for $z < 0$, and N' for $z > 0$. By integrating relation (1) and using well known representation of θ function

$$\theta(\alpha) = \frac{1}{2\pi i}\int_{-\infty}^{+\infty}\frac{\exp(-i\alpha\tau)}{\tau - i\varepsilon}d\tau \tag{2}$$

we obtain the result

$$A_{fi} = a_{fi} i(2\pi)^2\delta(q_x)\delta(q_y)\frac{N - N'}{q_z} \tag{3}$$

Wave numbers k and k' must be evaluated for particles in N and N' refractive media, and not for particles in free space. For particles of energy ω in media N the wave number is $k = (\omega/c)n$, where $n = 1 + Na_{fi}(0^o)/k_i^2$ is index of refraction, $a_{fi}(0^o)$ is the forward scattering amplitude and k_i is the wave number of particles in free space. Eq. (3) does not depend on the type of particles involved in the scattering processes and will be the basis of all our further investigations.

For photons we can obtain the reflection and Snell refraction laws and also the reflection and refraction coefficients $P^{refl}_{\gamma\to\gamma}$ and $P^{refr}_{\gamma\to\gamma'}$. We can extend this to the situation where photons incident from medium N scatter at the interface between the N and N' media, and both photons and weakly interacting vector bosons are emitted. For the process in which weakly interacting vector bosons are emitted into medium N', in analogy with the similar process in conventional electrodynamics, we define the vector boson refraction coefficient

$$P^{refr}_{\gamma\to\xi'} = \frac{k_{\xi' z} \mid A^{refr}_{\xi'\gamma} \mid^2}{k_{\gamma' z} \mid A^{refr}_{\gamma'\gamma} \mid^2 + k_{\gamma z} \mid A^{refl}_{\gamma\gamma} \mid^2 + k_{\xi' z} \mid A^{refr}_{\xi'\gamma} \mid^2 + k_{\xi z} \mid A^{refl}_{\xi\gamma} \mid^2} \tag{4}$$

In Eq. (4) $A^{refl}_{\gamma\gamma}$ and $A^{refr}_{\gamma'\gamma}$ are the total amplitudes for the reflection and refraction of the photon beam, and are obtained from Eq. (3) by inserting $q_z = 2k_\gamma \cos\theta_i$ and $q_z = k_\gamma \cos\theta_i - k_{\gamma'} \cos\theta_{\gamma'}$, respectively. θ_i and $\theta_{\gamma'}$ are the angles of incident and refracted photon beams defined relatively to the normal on the plane surface between two media. k_γ and $k_{\gamma'}$ are wave numbers of photons in N and N' refractive media, and $k_{\gamma z}$ and $k_{\gamma' z}$ are their projections on the z-axis. The total scattering amplitudes $A^{refl}_{\xi\gamma}$ and $A^{refr}_{\xi'\gamma}$ for the processes in which weakly interacting vector bosons are emitted into N and N' refractive media could be obtained from Eq. (3) by inserting $q_z = k_\gamma \cos\theta_i - k_\xi \cos\theta_\xi$ and $q_z = k_\gamma \cos\theta_i - k_{\xi'} \cos\theta_{\xi'}$, respectively. k_ξ and $k_{\xi'}$ are wave numbers of weakly interacting vector bosons emitted at θ_ξ and $\theta_{\xi'}$ angles into N and N' refractive media, and $k_{\xi z}$ and $k_{\xi' z}$ are their projections on the z-axis.

The main results of our investigations will become clearer if we make some approximations that will simplify Eq. (4). First we will assume that the rest masses of the weakly interacting vector bosons are very small compared to their total energies. If we further assume that the angle of incidence $\theta_i \approx 0^o$ we eliminate the dependence of scattering amplitudes a_{fi} on initial polarization and scattering angles. For the ratio of relevant scattering amplitudes we can make a reasonably good approximation $|a_{\xi\gamma}|^2/|a_{\gamma\gamma}|^2 \approx \alpha_\xi/\alpha << 1$. In that case from Eqs. (3) and (4) we obtain

$$P^{refr}_{\gamma\to\xi'} \approx \left(\frac{\alpha_\xi}{\alpha}\right) \frac{4n_\gamma n_{\xi'}}{(n_\gamma - n_{\xi'})^2} \left(\frac{n_{\gamma'} - n_\gamma}{n_{\gamma'} + n_\gamma}\right)^2 \tag{5}$$

where n_γ and $n_{\gamma'}$ denote indices of refraction for photons, and $n_{\xi'}$ for new vector bosons, respectively; α_ξ and α are dimensionless constants of interaction for new vector bosons and photons with electrons, respectively.

From Eq. (5) we see that if photons were incident from the high vacuum region, the number of light vector bosons produced in the scattering process at the surface between two refractive media could be very high, because $n_{\xi'} \approx 1$ and therefore $P^{refr}_{\gamma\to\xi'} \propto 1/(n_\gamma - 1)^2$, and for high vacuum $n_\gamma \approx 1$. On the other hand the intensities of new vector bosons emitted in the reflection processes are always by an approximate factor α_ξ/α lower than the intensities of the reflected photons. Therefore we would be most interested in refraction processes in which photons are absorbed and new vector bosons are emitted in the forward direction. Sensitivity of our experimental method is limited by the masses of light vector bosons produced in the scattering process, because for non-negligible masses the change of the z-component of the wave vector is $q_z = k_{\gamma z} - k_{\xi' z} \approx [n_\gamma - 1 + (m_\xi c^2/E_\gamma)^2/2]$ for $\theta_i \approx 0^o$ scattering.

For the experimental investigations of weakly interacting light vector bosons we propose the "shining light through the wall" type of experiment. The initial photon from the laser is incident from the high vacuum region and scatters at a plane surface of a thin glass plate with an index of refraction $n_{\gamma'}$ for photons. The photon beam is then blocked to eliminate everything except the light vector bosons, which pass through because of their extremely weak interaction with ordinary matter. The light boson then interacts at the surface between another glass plate and the high vacuum region to produce a photon, whose detection is the signal for the production of the light boson. A single photon counting system using a low noise photomultiplier could be very efficient for the detection of photons. The sensitivity of the system can be increased if we use L and L' glass plates in front and behind of the blocking piece. In order to minimize the absorption of photons in the glass, the plates should be tilted at the Brewster angle. The expected number of photons recorded in the single photon counting system will be

$$N_c = \varepsilon L P^{refr}_{\gamma\to\xi'} L' P^{refr}_{\xi'\to\gamma} N_{laser} \tag{6}$$

where ε is the efficiency of the photomultiplier, N_{laser} is total number of photons emitted from the laser during the experiment, and $P^{refr}_{\xi'\to\gamma}$ is the coefficient for the refraction process, given by an expression similar to Eq. (5), in which weakly interacting vector bosons produce photons.

To estimate the sensitivity of our experiment we will assume that the pulsed laser emits the 532 nm wavelength photons with the total energy of 30 mJ per 10 nsec width pulse at the repetition rate of 20 Hz. We will further assume $\varepsilon = 0.25$, $L = L' = 1000$, $n_\xi = n_{\xi'} = 1$,and $n_{\gamma'} = 1.9$. Index of refraction n_γ will be expressed as the function of residual pressure in the experimental apparatus. Using coincidence techniques we can expect the background to be less than 10 counts during 10^6 seconds of laser operation and then from Eqs. (5) and (6) we easily calculate limits for α_ξ/α at different vacuum values. Results of our estimates are shown with the full line in Fig. 2.

Present limits for several weakly interacting vector bosons are also shown in Fig. 2. For even modest vacuums of $\approx 10^{-8}$ Torr the upper limits on coupling constants for paraphotons [7] with rest masses of $m_\Gamma \leq 10^{-7}$ eV could be lowered by an enormous factor of $\approx 10^{28}$. For very high vacuums of $\approx 10^{-12}$ Torr, which are still available in earth-bound laboratories, the upper limit on coupling constants for leptonic photons [8] could be improved by a factor of $\approx 10^4$.

We have also made an estimate for detecting some possible gravitational effects. If a gravity theory would allow the existence of a vector field then antigravitons [9], i.e. spin 1 gravitational field quanta, could be detected in our apparatus. The probability that the transition between the two electron states will proceed by emission of gravitational, rather than electromagnetic, radiation is typically of order $\alpha_{grav}/\alpha \approx Gm^2/e^2$, where G is gravitational constant, and m and e are electron mass and charge respectively. In that case antigravitons could be detected even at vacuums of $\approx 10^{-8}$ Torr.

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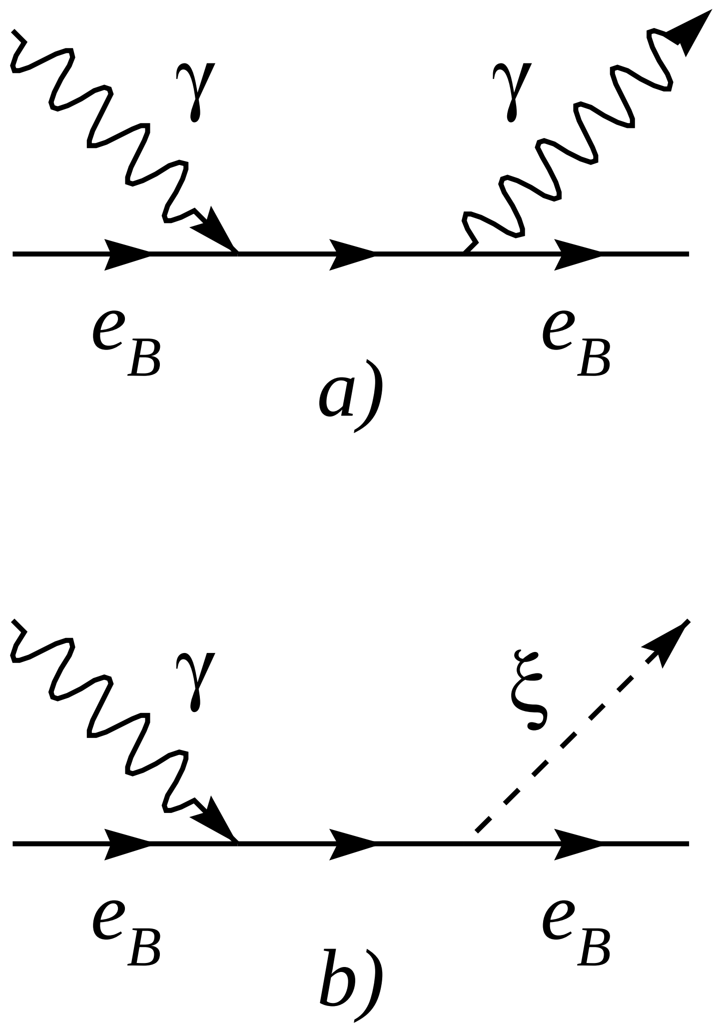
Fig. 1. Feynmam diagrams for the elastic scattering of photons on atomic electrons. ξ represents weakly interacting light bosons.

Fig. 2. Sensitivity of the proposed method for different vacuum values; corresponding masses of light bosons are shown on the upper scale of the x-axis. Shaded regions are excluded by the experiments. Exclusion region for paraphotons was obtained from ref. [7]. Upper limit on the leptonic photon coupling constant was taken from ref. [8].


γ
γ
e_B
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a)
γ
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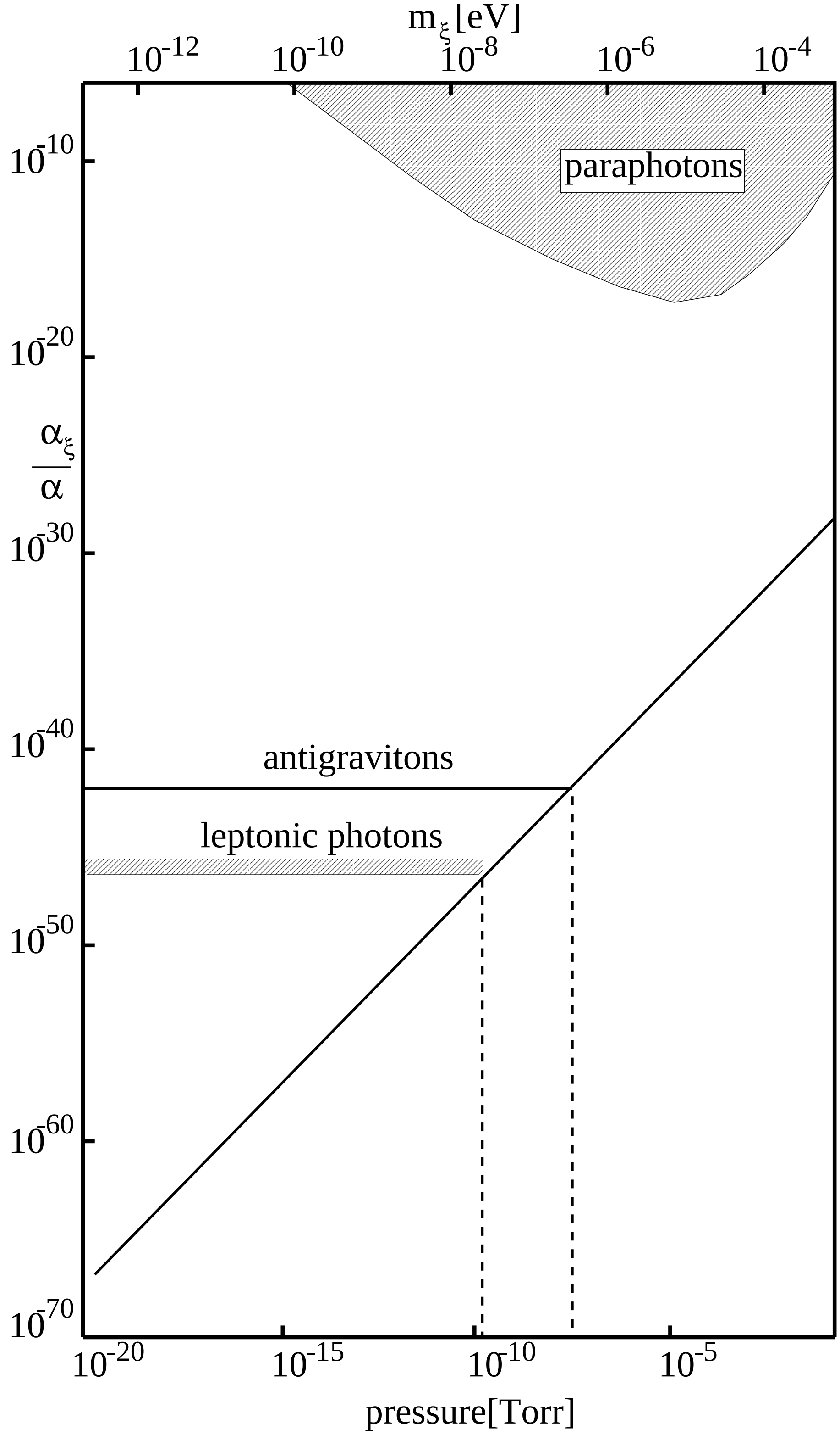

m_ξ [eV]
10^-12
10^-10
10^-8
10^-6
10^-4
paraphotons
10^-10
10^-20
α_ξ / α
10^-30
10^-40
antigravitons
leptonic photons
10^-50
10^-60
10^-70
10^-20
10^-15
10^-10
10^-5
pressure[Torr]